High Electrode Loading Electric Vehicle Cell

Dr. Mohamed Taggougui

June 1st, 2020

Project ID# bat332

Timeline

- Project start: 15 June 2016
- Project end: 14 August 2019
- Percent complete: 100%

Budget

- Total project funding
- DOE share: $3,499,297
- 24M share: $3,499,297

- Funding received in FY19
  - DOE share: $502,390
  - 24M share: $913,324

Barriers

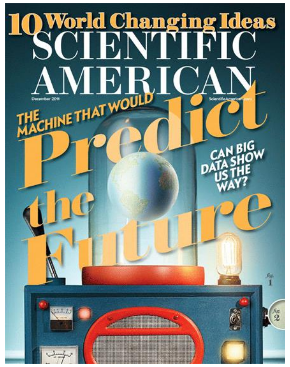
- Cost – current costs are three times too high on a kWh basis
- Performance – High energy density battery systems are needed to meet both volume and weight targets
- Abuse tolerance, reliability, ruggedness – many Li-ion batteries are not intrinsically tolerant to abusive conditions

Partners

- 24M Technologies - LEAD

- 2010: company founded
  - Yet-Ming Chiang, Throop Wilder, W. Craig Carter
- 2014: automated line running
  - 32,000 sq.ft. facility
  - 40+ employees
- IP Portfolio: 60+(31) issued patents, 90+ pending
- Funding Events: $130M+ in equity
  - Three Financial Investors
  - Four Industrial Partners (GPSC/PTT, Kyocera, Itochu, etc.)
- DOE Grants:
  - $4.5M to date (Vehicle Technology, ARPA-E)
  - ARPA-E Grant: $1.2M thought 2019 (Lithium Metal)
  - USABC Awards: $7M through mid 2019 (EV)

Recognition



Company Facts: Reinventing Lithium-Ion Manufacturing with SemiSolid Electrodes

DIFFERENTIATED TODAY: SEMISOLID TECHNOLOGY CREATES SUSTAINABLE COST ADVANTAGE IN $30B MARKET

> 25% lower cell cost via reduced bill of materials and simplified manufacturing process
> Half the capital cost per unit of manufacturing capacity installed ($/MWh)
> Innovative system designs leveraging large-format cells to reduce balance of system costs

COMMERCIALIZATION UNDERWAY: STRATEGIC PARTNERS BUILDING FACTORIES TO EXPLOIT TODAY'S TECHNOLOGY

> 100MWh/yr pilot factory in 2020, with potential to rapidly scale
> Major battery manufacturer signed on as EV development partner for high-energy density products
> Significant R&D funding via high-profile government programs

TRANSFORMATIVE TOMORROW: SEMISOLID PLATFORM ENABLES UNIQUE APPROACHES TO HIGH PERFORMANCE

> Achieve solid-state battery performance with significantly lower risk using dual electrolyte system
> Leverage differentiated silicon anode approach to high-energy density systems - move to 1st position
> Rapidly scale-up new technologies by integrating into existing 24M high volume manufacturing processes

Company Facts: 24M Commercialization Under Way

- Kyocera starts mass production late 2020 in Shiga, Japan

KYOCERA Global

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News

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Kyocera and 24M Develop World's First SemiSolid Lithium-ion Battery System with Improved Safety, Longer Life, and Lower Cost

Plans to Build Full-Scale Mass Production System Following Initial Success with Pilot

January 6, 2020 | Japan

KYOTO, Japan and CAMBRIDGE, Mass. — January 6, 2020 — Kyocera Corporation (President: Hideo Tanimoto) and 24M (President & CTO: Naoki Ota) announced today that Kyocera has formally launched its residential energy storage system, Enerezza, the world's first system built using 24M's novel SemiSolid electrode manufacturing process. In addition, Kyocera has extended its commitment to 24M's unique manufacturing platform with plans to start full-scale mass production in the fall of 2020.

Enerezza

Next-Generation SemiSolid Lithium-Ion Battery System "Enerezza," power conditioner (left), battery unit (middle), and remote controller (right)

In June 2019, Kyocera began pilot production of 24M's SemiSolid battery technology to validate its use in residential energy storage systems in the Japanese market. Based on the successful pilot, Kyocera recently rolled out its full Enerezza product line — a 24M-based residential energy storage system available in 5.0 kWh, 10.0 kWh, and 15.0 kWh capacities designed to meet diverse customer needs.

"Kyocera and our customers benefit from long battery life, unparalleled safety, and the low-cost approach enabled by 24M's unique manufacturing process," said Toshihide Koyano, Deputy General Manager of Corporate Solar Energy Group at Kyocera. "At Kyocera, we believe that 24M's SemiSolid technology is the emerging standard for lithium-ion battery manufacturing. We are delighted to be the first company to deliver residential energy storage products using 24M's novel process."

24M's innovative manufacturing process delivers market-leading price-performance. SemiSolid electrodes use no binder, mixing electrolyte with active materials to form a clay-like slurry with unique attributes. As a result, the 24M process eliminates the need for a significant amount of inactive materials and capital-intensive processes like drying and electrolyte filling, thus dramatically reducing manufacturing cost.

"Kyocera's launch of the Enerezza residential energy storage product line marks a significant milestone for 24M," said Naoki Ota, President and CTO of 24M. "After many years of hard work, our technology is commercially available thanks to our dedicated partner Kyocera.

- GPSC/PTT Installs mass production equipment built by Hitachi late 2020

Green Car Congress

Energy, technologies, issues and policies for sustainable mobility

GPSC to build plant for 24M semi-solid batteries in Thailand; 30 MWh to start, 100 MWh in 2021

20 February 2020

Global Power Synergy PLC (GPSC) is building a battery manufacturing facility in Thailand using 24M's novel SemiSolid lithium-ion technology (earlier post). GPSC is the main power and utility company of PTT Group.

24M

- Overall Objective:
  - Develop and demonstrate EV-capable cells based on 24M's semi-solid electrode technology

- Objectives This Period:
  - Ship phase 3 deliverable cells to ANL
  - Increase the solids loading of active materials
  - Improve cycle and calendar life of high nickel content cathode active materials
  - Confirm superiority of semi-solid electrode abuse tolerance

- Impact:
  - Demonstrate feasibility of low cost EV-capable cells based on 24M's semi-solid electrode

Milestones/Deliverables

Description of Milestone or Deliverable	Target Date	Status
Kick-Off	6/15/2016	Completed
Baseline Cell Gap Analysis Completed	12/14/2016	Completed
Gen1 Safety Design Review	1/25/2017	Completed
Cost Model Alignment	3/16/2017	Completed
Gen2 Cathode Active Material Down-selection	6/14/2017	Completed
Anode Active Material Down-selection (2-3 materials)	6/14/2017	Completed
Phase 1 Deliverables (GO/NO GO) (D1.1)	6/14/2017	Completed
Gen2 Electrolyte Lock (RT Life + HT stability)	8/4/2017	Completed
High vol% Loading Cathode	10/30/2017	Completed
Gen2 Alloy Anode Blend Formulation	11/29/2017	Completed
Next Gen Coating Process Proof-of-Principle	12/27/2017	Completed
Gen3 Electrolyte Lock	1/22/2018	Completed
Gen2 Safety Design Review	3/16/2018	Completed
Cathode Material Lock	6/14/2018	Completed
Anode Material Lock	6/14/2018	Completed
Active Materials Lock	6/14/2018	Completed
Phase 2 Deliverables (GO/NO GO) (D2.1)	6/14/2018	Completed
Next Gen Coating Process Down-Select	9/14/2018	Completed
Gen3 Cell Safety Design Review	12/14/2018	Completed
Final Electrolyte Lock	12/14/2018	Completed
Deliver >250cm^2 footprint Cells (D3.1)	12/14/2018	Completed
Phase 3 Deliverables (GO/NO GO) (D3.2)	4/14/2019	Completed
Cost Optimized Cell Designs	5/14/2019	Completed
Program Conclusion	6/14/2019	Completed

Mixing

Coating & Drying

Solvent Recovery

Slitting

Press/Calendar

Electrode Creation

		Solvent Recovery								
Anode	Mix	Coat	Dry	Inspect	Slit	Clean	Calendar	Die Punch	Clean	Vacuum Dry
Cathode	Mix	Coat	Dry	Inspect	Slit	Clean	Calendar	Die Punch	Clean	Vacuum Dry
		Solvent Recovery								

Cell Assembly

Stack	Weld	Insert	Electrolyte

24M SemiSolid Li-ion Manufacturing:
- Substantially fewer steps
- No drying, no thermal processes
- Single liquid as solvent, carrier and final electrolyte

24m

Electrode Creation

Anode	Mix	Coat
Cathode	Mix	Coat

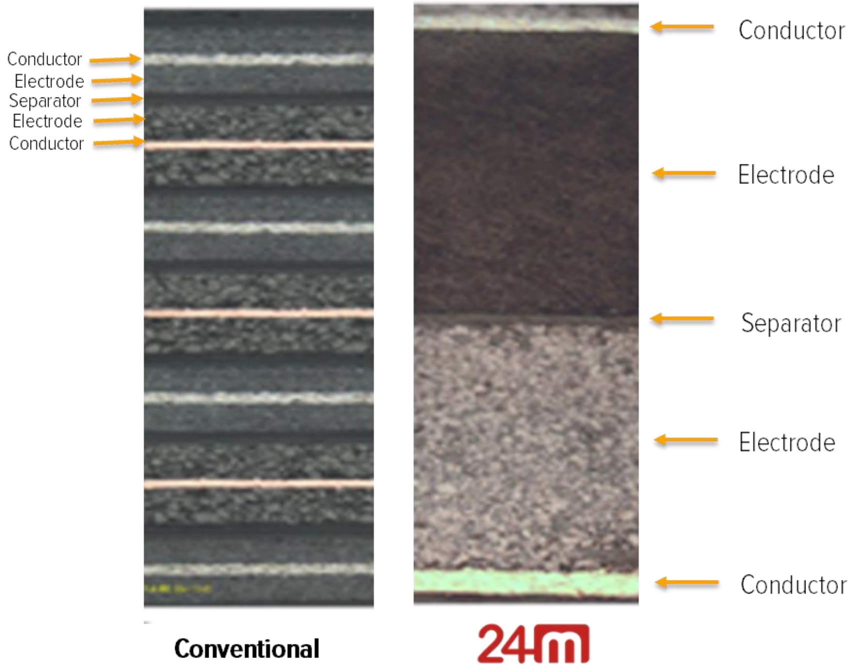
Cell Assembly

Stack	Weld	Insert

Cambridge, MA

Half the capital investment, lower labor, utilities and floor space

Cell Design Advantages



2-3.5mAh/cm^2 VS 7-14mAh/cm^2

60-110 microns VS 300-500 microns

25% BOM Cost Reduction

Components		24M BOM Advantage: Conventional	24m
Cathode	NMC	100%	----
	Carbon	100%	----
	Binder	100%	-100%
	Electrolyte	100%	-4%
	Al. Foil	100%	-61%
	NMP	100%	-100%
Anode	Graphite	100%	----
	Carbon	100%	----
	Binder	100%	-100%
	Electrolyte	100%	-12%
	Copper foil	100%	-63%
Package	Separator	100%	-82%
	Pouch	100%	-10%
	Tab/Tape	100%	-10%
TOTAL:		100%	-25% to 40%

Structural BOM advantage due to unique SemiSolid thick electrode

Technical Accomplishment to Date – FY19

- Shipped large size NMC811 52Ah Phase 3 deliverable cells to National labs for independent testing,
- Phase 3 deliverable cells completed 565 C/3 cycles and projected to achieve more than 1000 cycles before reaching EOL,
- Phase 3 deliverable cells achieved 276Wh/kg nominal specific energy @ C/3 discharge rate,
- Phase 2 deliverable cells met USABC DST cycle life requirement – 1030 cycles to EOL,
- Phase 3 deliverable cells achieved an impressive EUCAR 2 in overcharge to 200%SOC and EUCAR 4 in mechanical internal short circuit,
- Projected phase 3 deliverable cells COGS to be lower than $100/kWh at EOL.

Shipped Phase 3 Deliverable Cells to ANL: NMC811/Graphite

SPECIFICATION	
Nominal Capacity	2.9 Ah
Peak Discharge Power Density, 30 s Pulse	2200 W/L
Peak Specific Discharge Power , 30 s Pulse	800 W/kg
Peak Specific Regen Power , 10 s Pulse	300 W/kg
Energy Density @ C/3 Discharge Rate	**647 Wh/L**
Specific Energy @ C/3 Discharge Rate	**288 Wh/kg**
Areal Capacity	9.7 mAh/cm^2
Calendar Life	> 8 years
Cycle life - DST	> 1000
Normal Recharge Time	< 7
Nominal Roundtrip Energy Efficiency, C/3 rate	> 92%
Safety (UN 38.3)	PASS
Maximum Operating Voltage (V)	4.2
Minimum Operating Voltage (V)	2.8
Maximum Self-discharge	<1.5%/month

24M Unique Single Pouch Structure

Shipped Phase 3 Deliverable Cells to ANL: NMC811/Graphite

SPECIFICATION

Nominal Capacity	52 Ah
Number of Unit Cells	18
Peak Discharge Power Density, 30 s Pulse	2200 W/L
Peak Specific Discharge Power , 30 s Pulse	800 W/kg
Peak Specific Regen Power , 10 s Pulse	300 W/kg
Energy Density @ C/3 Discharge Rate	**548Wh/L**
Specific Energy @ C/3 Discharge Rate	**276 Wh/Kg**
Areal Capacity	9.7 mAh/cm^2
Calendar Life	> 8 years
Cycle life - DST	> 1000
Normal Recharge Time	< 7
Nominal Roundtrip Energy Efficiency, C/3 rate	> 92%
Safety (UN 38.3)	PASS
Maximum Operating Voltage (V)	4.2
Minimum Operating Voltage (V)	2.8
Maximum Self-discharge	<1.5%/month

Single Cells in Pouch Structure

Phase 3 Deliverable Cells – Initial Performance

Gen2 Cell Design

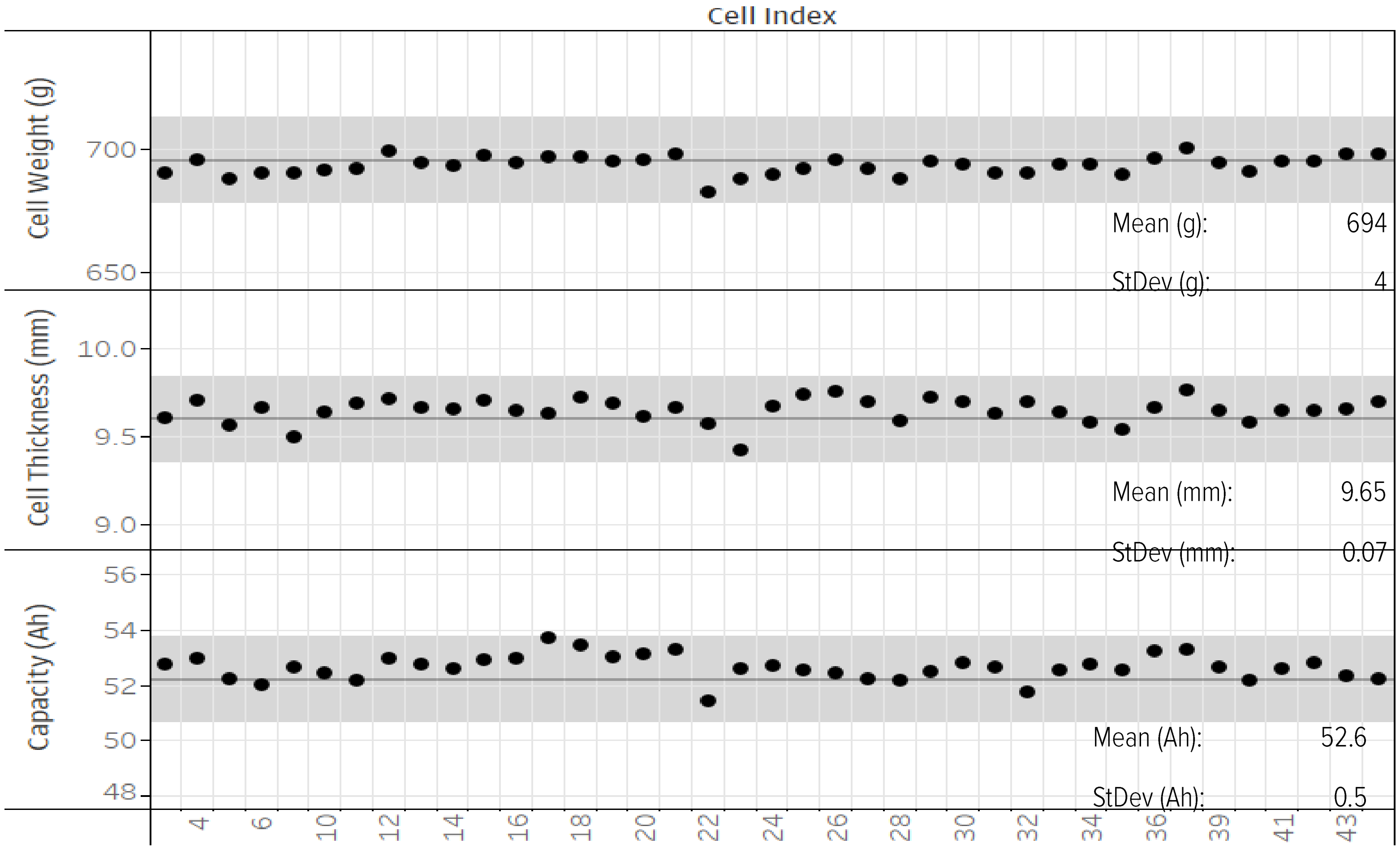
- 18 layers
- Cathode area: 304 cm^2
- Cell capacity: 52 Ah
- Areal capacity: 9.7 mAh/cm^2

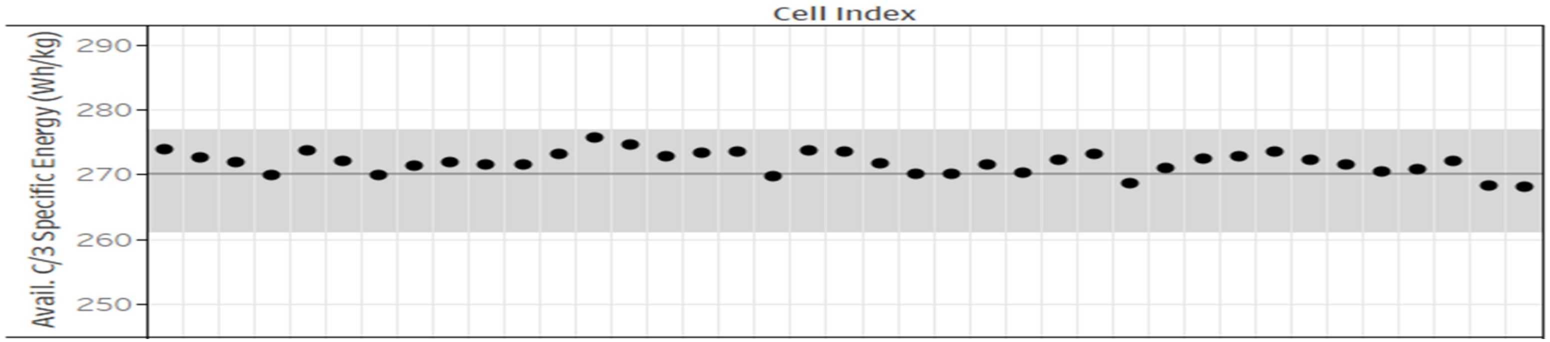
Testing Conditions

- CCCV/4 charge, CC/3 discharge, between 2.8-4.2V

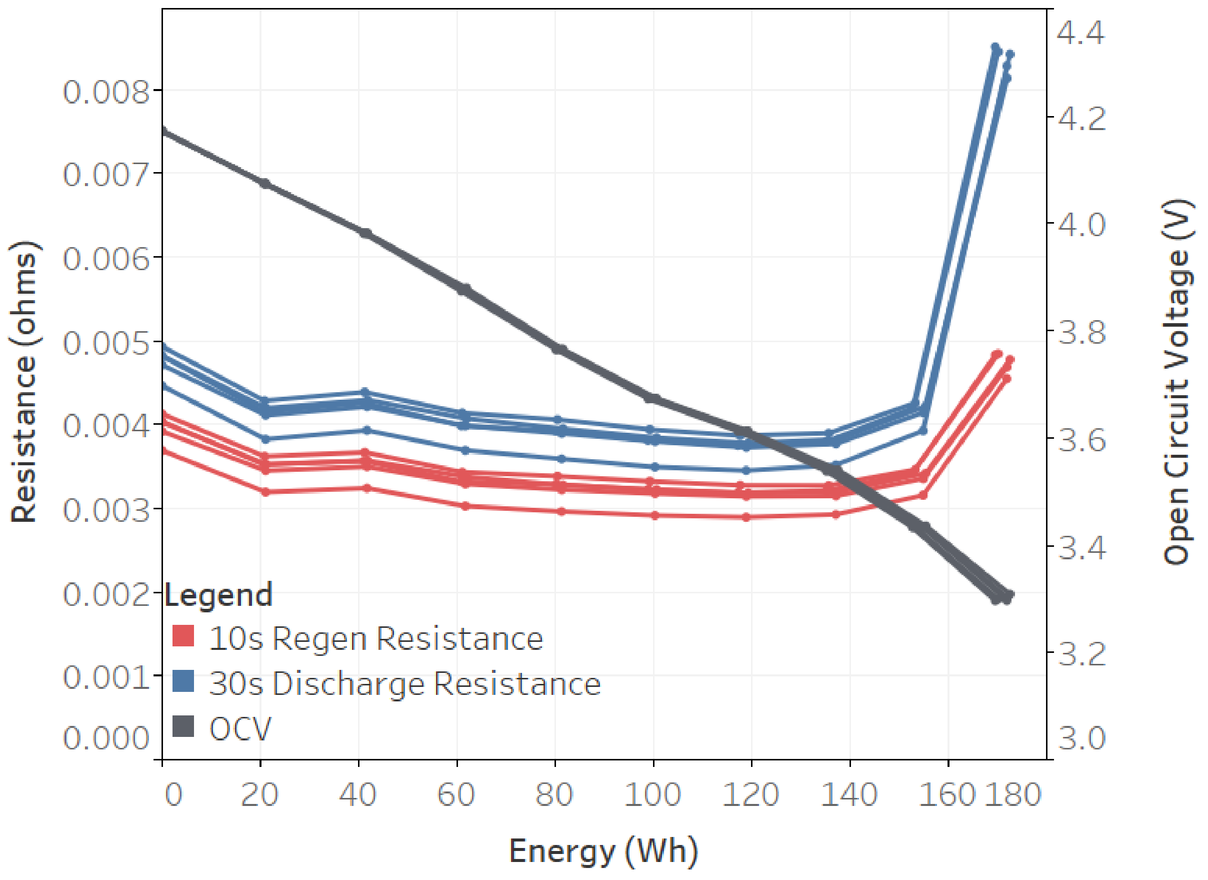
Total cell Specific Energy: 272 Wh/kg
Stack Level Specific Energy: 281 Wh/kg

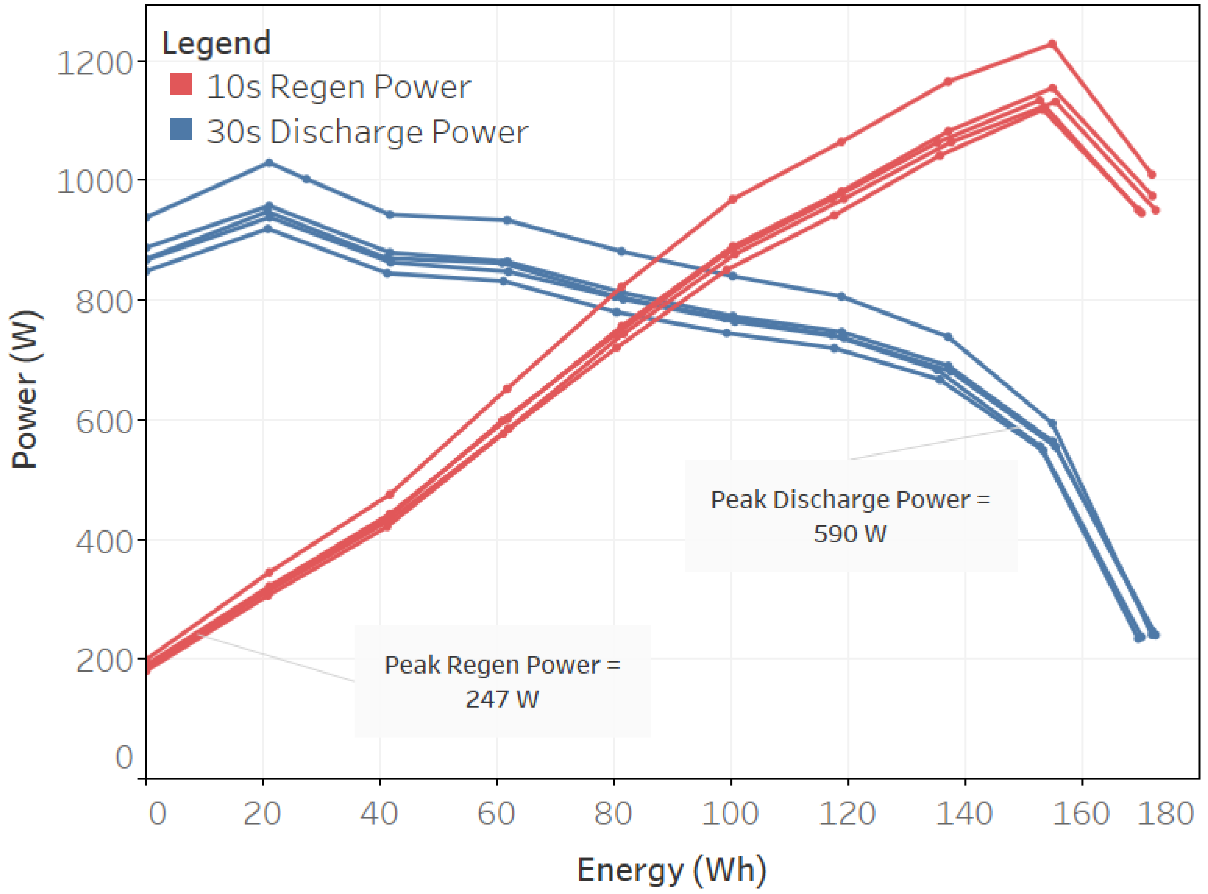
Gravimetric packing efficiency: 96.6%





Phase 3 Deliverable Cells – Initial Performance, HPPC Characterization (Vmin: 2.7V, Vmax: 4.3V)



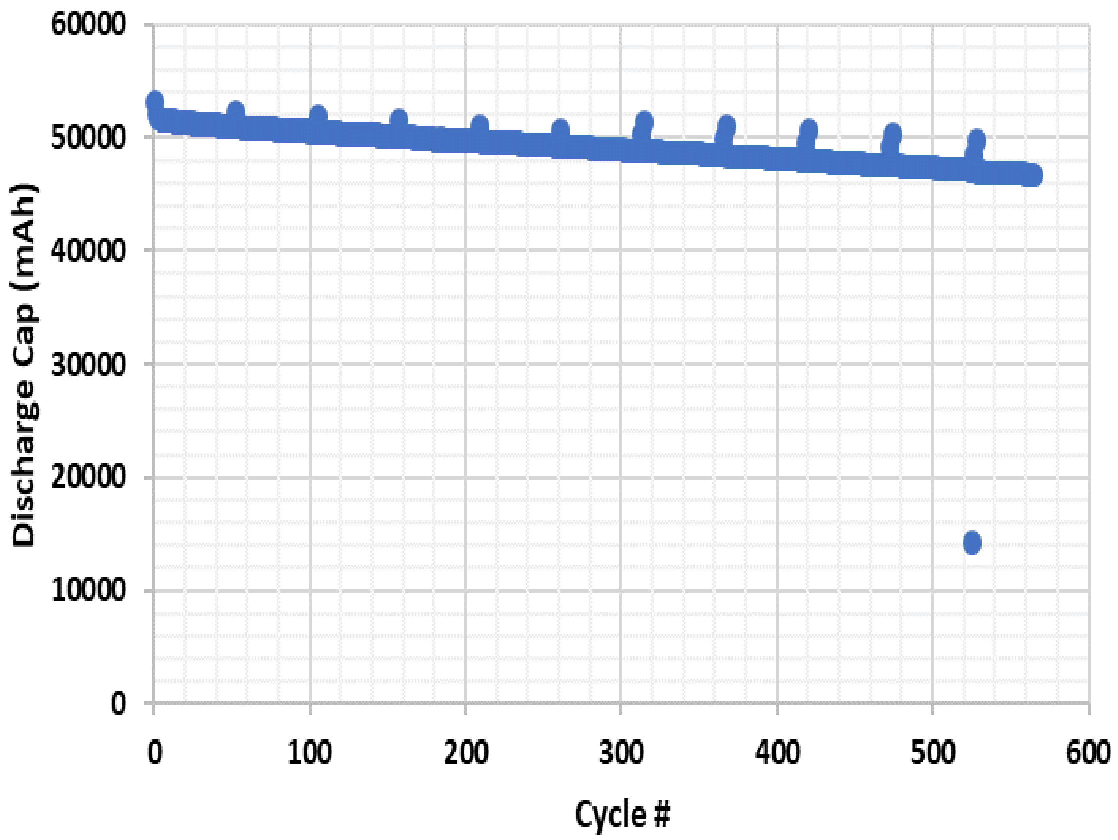


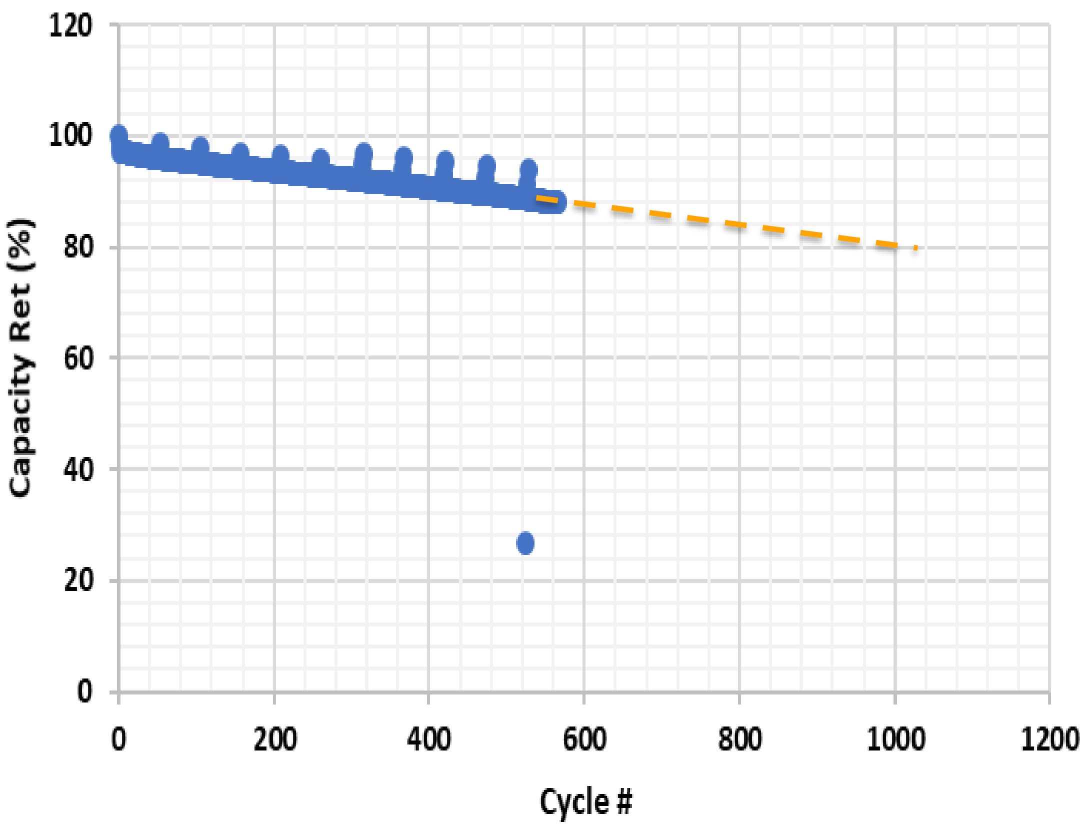
Peak Discharge power Density (30 sec) (W/L): 1730 ± 70. Peak Specific Discharge Power (30 sec) (W/kg): 850 ± 30
Peak Specific Regen Power (10 sec) (W/kg): 360 ± 15

24m

Phase 3 Deliverable Cells: Achieved more than 500 cycles with NMC811 semisolid cathode

- Duty cycle : C/4 Charge to 4.2V, C/3 Discharge to 2.8V, 30^{0}C Cycling temperature. C/10 RPT capacity check every 50 cycles
- All cells started testing without prior aging

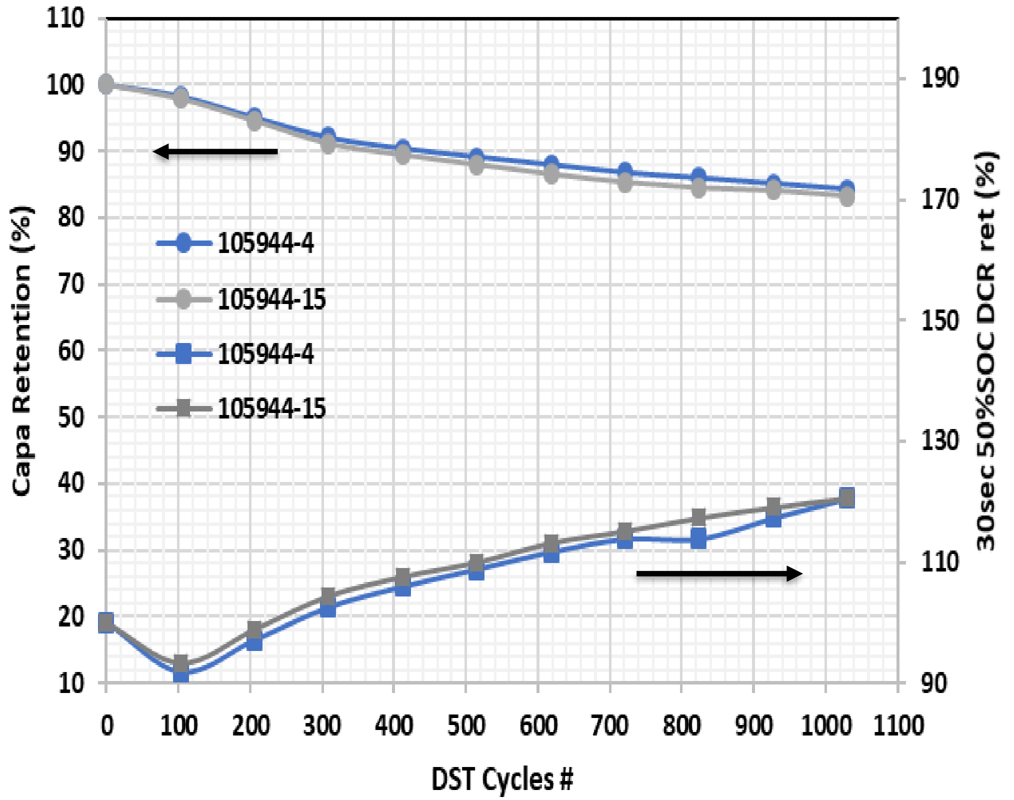


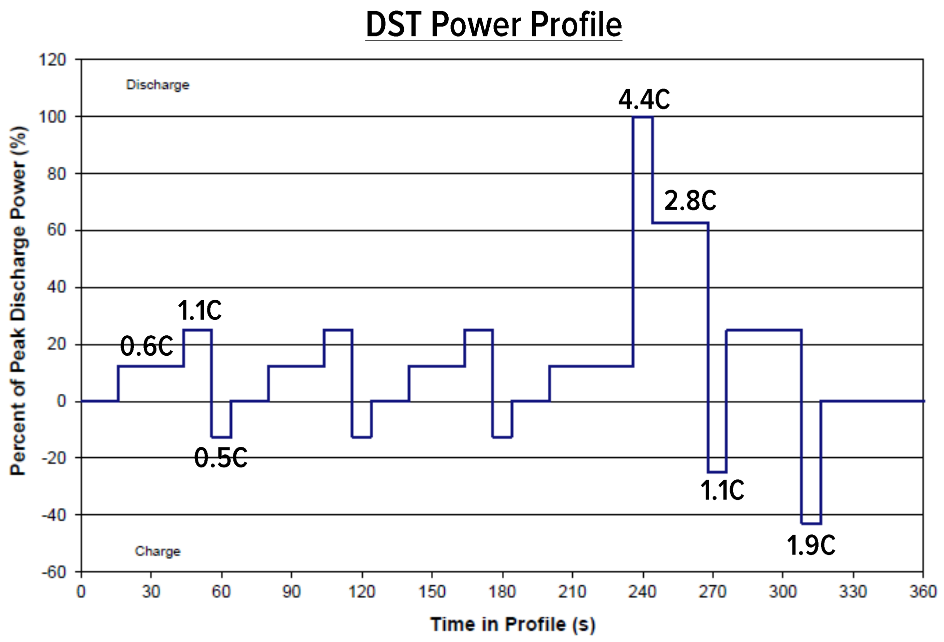


Phase 3 deliverable cells projected to achieve 1000 cycles before reaching EOL

Phase 2 Deliverable cells meet USABC DST cycle life requirement

- DST profile according to USABC EV manual (700W/kg)
- RPT completed every 31 days (103 cycles completed every 31 days)
- All cells started testing without prior aging





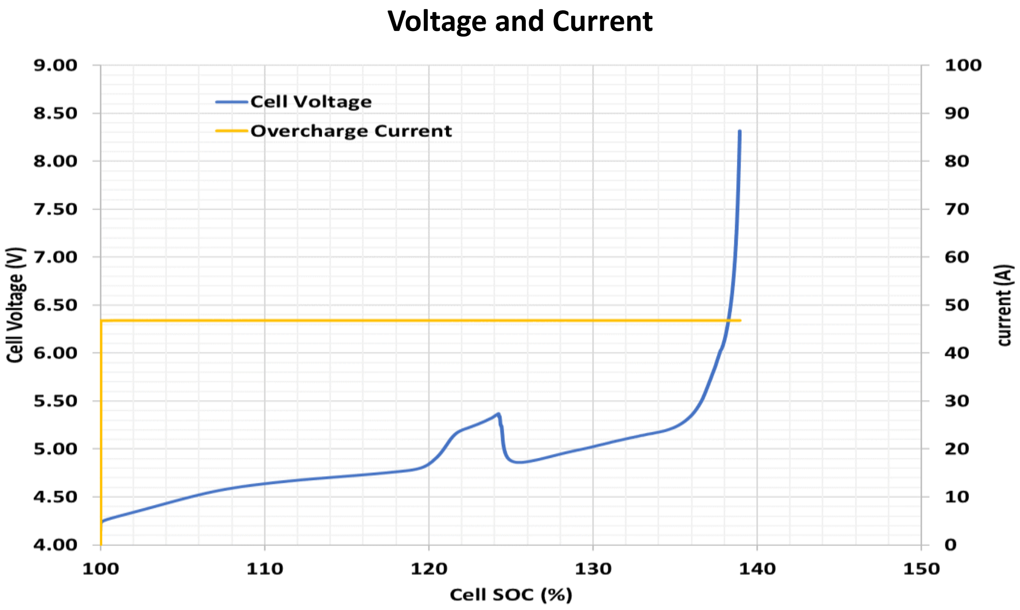
After 1030 DST cycles with NMC811 semisolid cathode: Capacity retention at 84% and 50%SOC 30sec discharge resistance increased only by 21%

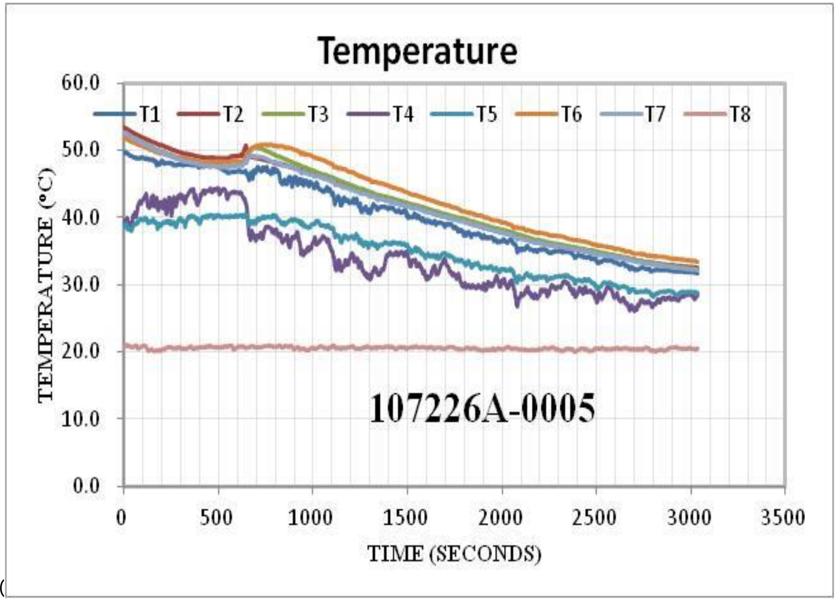
Phase 3 Deliverable Cells – Electrical & Mechanical Abuse Testing Summary

Reference	Test	# of cells tested	Results
Overcharge	1C to 200%SOC or 8.4V @ 60˚C	6	EUCAR2
External Short circuit	100%SOC (4.2V), 60˚C, 3.5mOhm	6	EUCAR2
Internal Short circuit – Pin penetration	100%SOC, 0.1mm, Voltage drop of ≤ 5mV	4	EUCAR4
Over-discharge	1C to voltage reverse voltage or 1C to 0.7V (20% the nominal voltage)	3	EUCAR2
Crush	100%SOC, 50%deformation or 200kN	2	EUCAR1
Thermal Stability	100%SOC, 5˚C/min ramp to 130˚C	4	EUCAR2
ARC to runaway	100%SOC, 0.02˚C/min to failure	2	160˚C onset temperature EUCAR5

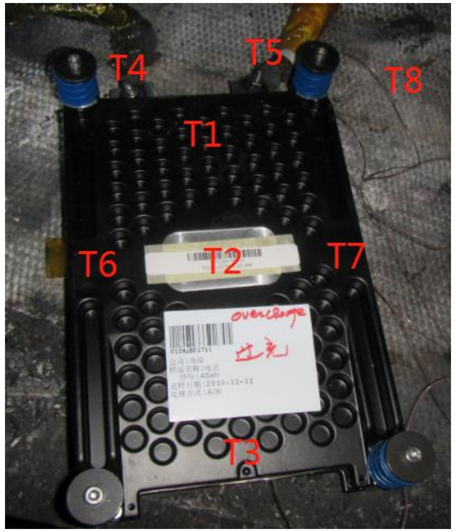
Exceptional Abuse Tolerance with High Energy Material NMC811

Phase 3 Deliverable Cells – Electrical Abuse : 1C Overcharge to 200%SOC @ 60˚C – EUCAR 2





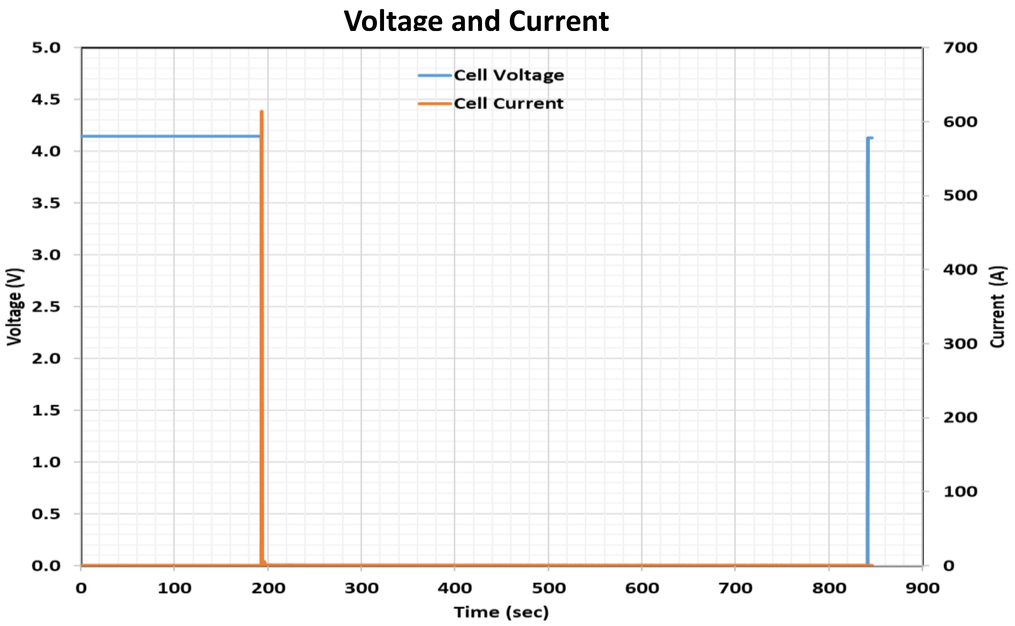
Before Test

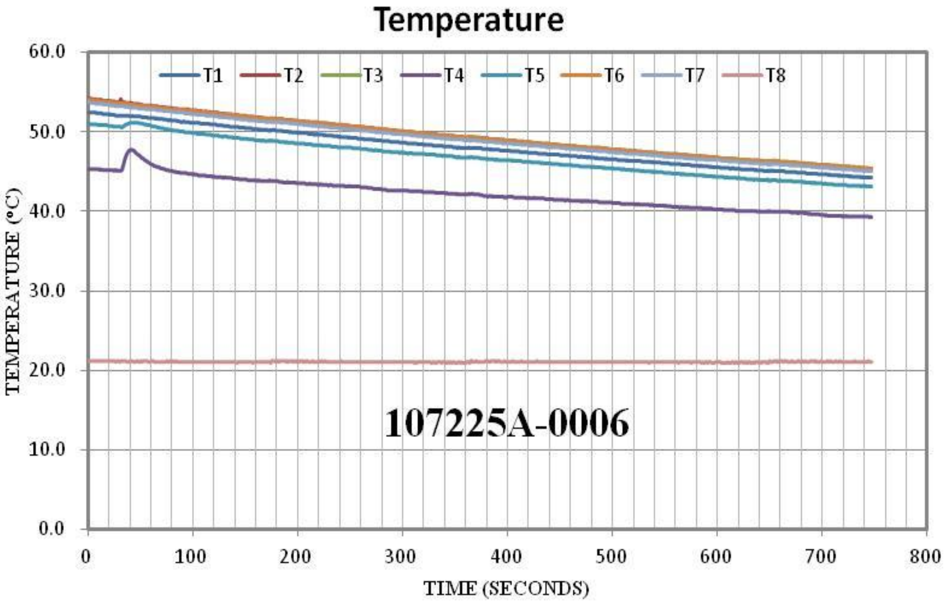


After Test

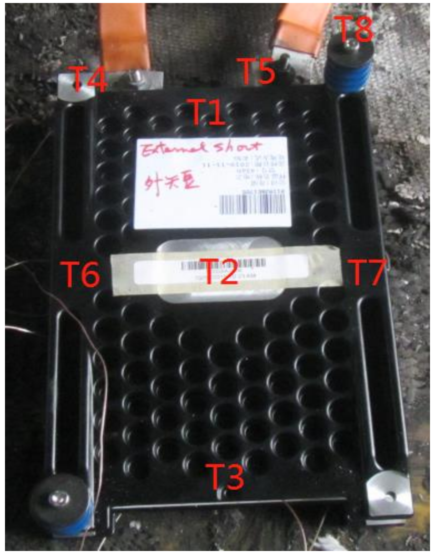
Cell venting: Did not vent
Venting SOC: Did not vent
Max T at venting: N/A
Max. T: 53.5^{o}C
Cell Did Not Vent, No Fire
EUCAR 2

Phase 3 Deliverable Cells – Electrical Abuse : 3.5mohm External Short, 100%SOC @ 60˚C – EUCAR 2

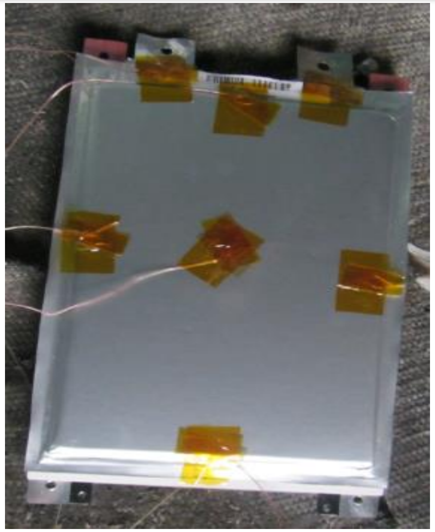




Before Test

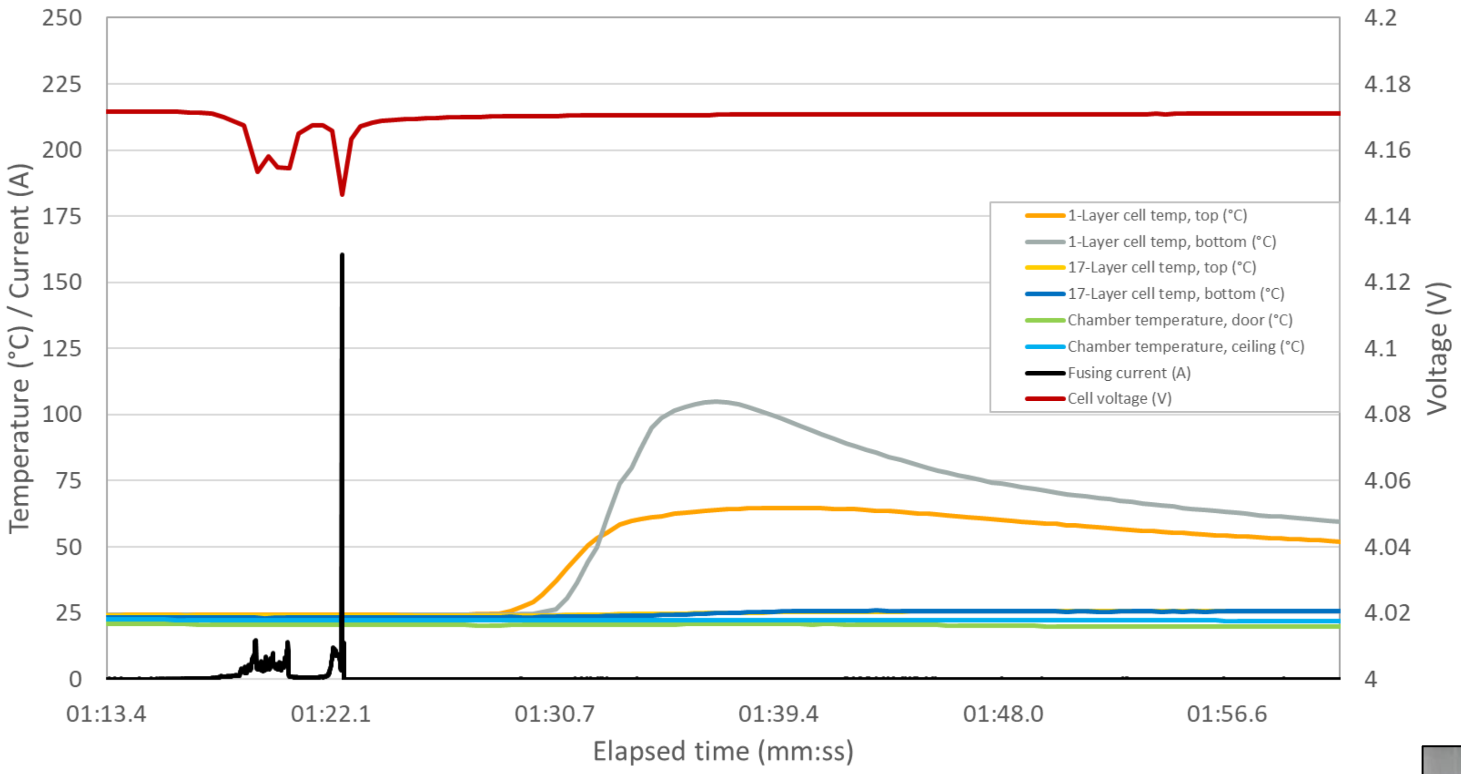


After Test



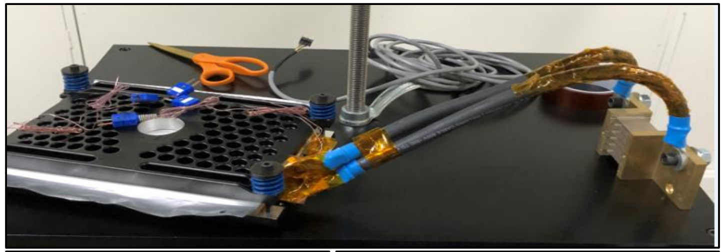
Cell venting: Did not vent
Venting SOC: Did not vent
Max T at venting: N/A
Max. T: 63°C
Cell Did Not Vent, No Fire
EUCAR 2

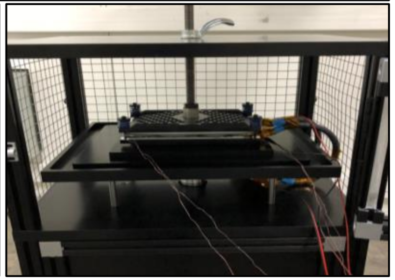
Phase 3 Deliverable Cells - Pin test (100%SOC, 8cm/sec, side, 25°C)



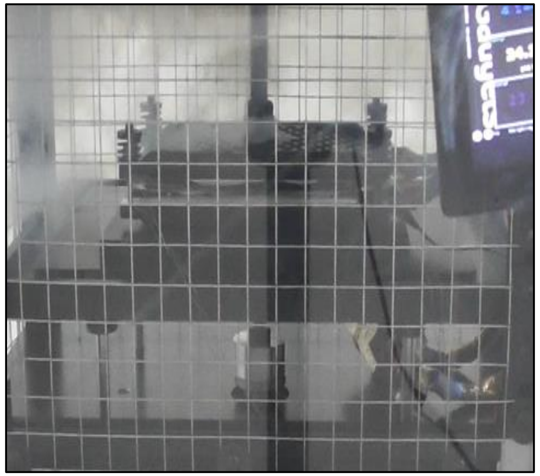
Fusing Current	160A
Cell Voltage before test	4.2V
Max Temperature	105°C (Unit Cell)
Time to max temperature	35sec
OCV After Test	4.14V
EUCAR level	4

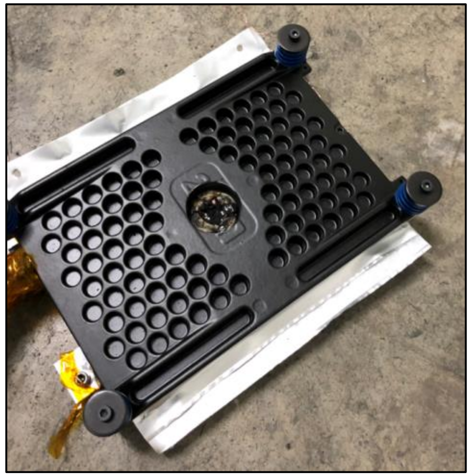
Before Test





After Test



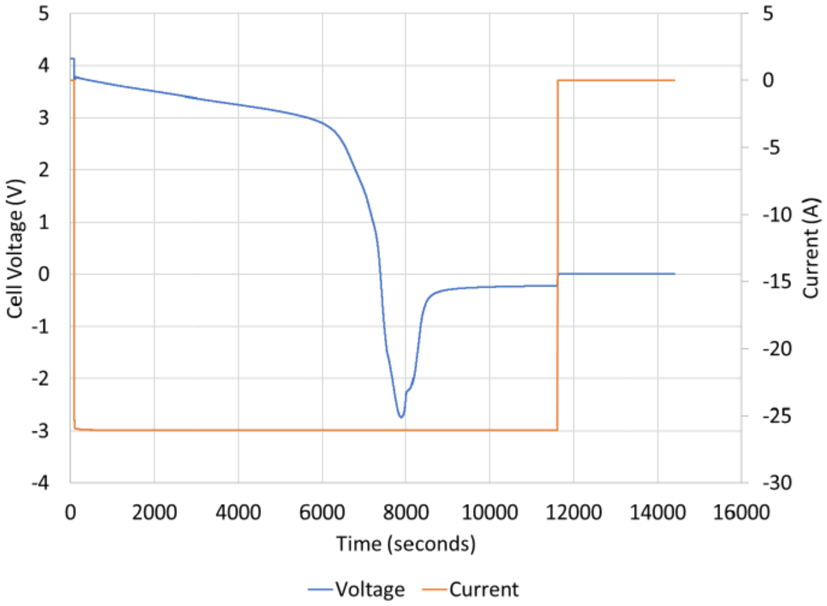


Overdischarge Abuse Testing:

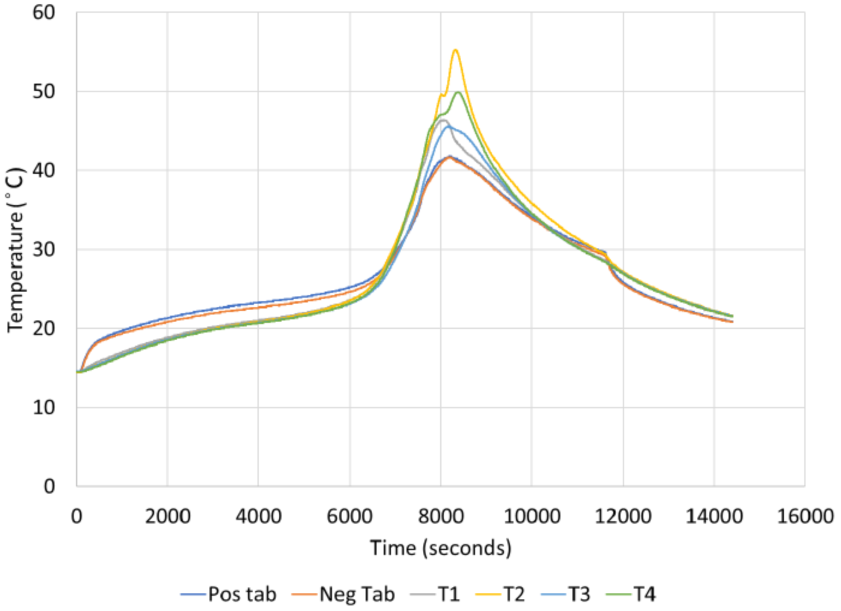
EUCAR 2

- Testing conditions
  - Test started with cell at 100%SOC and room temperature
  - C/2 Discharge
  - Compliance set at -20V

Voltage and current vs time



Temperature vs time



- No thermal runaway observed
- Some cell heating observed when cell goes into reversal
- Shortly after reversal cell voltage declines to near 0V
- Peak observed temperature 55 °C

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Argonne NATIONAL LABORATORY	Conduct electrical testing to verify the performance and life capability of deliverable cells vs. target performance
Sandia National Laboratories — Exceptional service in the national interest	Conduct abuse testing to verify the performance of deliverable cells vs. target performance

Remaining Challenges and Barriers

- Meeting Phase 3 EOL available energy requirements (350 Wh/kg & 750 Wh/L)
- Meeting Phase 3 EOL 3.2C fast charge requirement (80% in 15min),
- Meeting Phase 3 EOL Useable Energy @ -20^{0}C requirement (> 70%),
- Phase 3 deliverable cell design fast resistance increase in calendar life remain a challenge.

Substantial learning was gained during this program. Following those learnings, 24M has identified new categories (opportunities) to overcome the technical challenges encountered during this program. Overcoming these hurdles will enable a true ultra low-cost and fast charge automotive capable cell. The categories identified for significant value creation are,

1) Enable ultra Low-cost:
   a. Improve ultra thick low cobalt content cathode calendar life
   b. Recycling and reuse of in process lost active material
2) Enable fast charge:
   a. Develop a true bimodal active material, 10 to 1 ratio
   b. Develop an electrolyte formulation with conductivity above 12 mS/cm

“Any proposed future work is subject to change based on funding levels”

Summary

- Phase 2 deliverable cells met USABC DST cycle life requirement,
- Delivered phase 3 cells, 52Ah large size pouch format, to National labs for independent testing - further confirmation of the versatility of the semisolid electrode platform,
- Phase 3 deliverable cells delivered a nominal 276Wh/kg specific energy at BOL,
- Confirmed exceptional abuse tolerance of semi-solid NMC811 cathode at large format 52Ah size cell,
- Projected phase 3 deliverable cell COGS < $100/kWh at EOL,
- Identified technical opportunities to enable a true ultra low-cost and fast charge automotive capable cell using 24M proprietary SemiSolid manufacturing platform.